Ligado's Technical Response to Iridium's December 14 Letter

Summary:

This paper responds to Iridium's December 14 Technical Response[i] and its accompanying Aviation Analysis,[ii] which offered a criticism of Ligado's November 2 critique of Iridium's methodology[iii] and also for the first time raised aviation use case concerns. This submission responds to those issues in turn.

First, Iridium's defense of its methodology is flawed because the methodology uses an inappropriate propagation model and relies on analysis developed from different spectrum bands and different use cases.

- Iridium's continued use of the Hata-Okumura propagation model in analyzing Ligado's proposal is inappropriate. Hata-Okumura is designed for a base station height of 30-200 meters, but Iridium applies it to transmitter and receiver heights of just two (2) meters. In addition, Hata-Okumura is designed for distances of 1-20 kilometers, yet Iridium extrapolates losses in the range of 100-200 meters by combining Hata-Okumura and Free-Space Path Loss models. And finally, Hata-Okumura applies to frequencies in the range of 150-1500 MHz, but Iridium uses it for the spectrum at issue, 1626.5 MHz.

- Iridium also errs in relying on analysis developed for the CSMAC Working Group 1 ("WG-1") report[iv] as its basis for defending its propagation analysis and as justification for disregarding antenna polarization mismatch loss, head/body obstruction loss, building attenuation, and power control reductions. The WG-1 Report analyzed a different frequency band (1695-1710 MHz) and a completely different use case (protecting Federal meteorological fixed earth stations from spectrum sharing); as a result, the assumptions underlying the WG-1 Report's interference-analysis methodology are inapplicable in analyzing the potential effect of Ligado's proposed mobile ATC devices on Iridium's mobile terminals. Iridium's analysis fails to account for the differences between these very different scenarios.

Second, this paper analyzes each of the aviation use cases raised by Iridium in the December 14 Technical Response and demonstrates how each can be resolved.

Finally, this paper makes the important observation that if one were to accept Iridium's analysis (which the Commission should not), then *Iridium would not be able to operate in the presence of even a single one of the five million high-power satellite user terminals* authorized to operate in or adjacent to Iridium's spectrum. Ligado's proposed ATC out-of-band emission (OOBE) limit is as much as 15,000 times lower than the OOBE limit applicable to the mobile earth-station user terminals authorized to operate on the Ligado, Inmarsat, and Globalstar MSS networks. Thus, Ligado's 0.2 watt ATC devices will generate much lower OOBE into Iridium's receive band than existing Ligado satellite METs that could be operating at any time near an Iridium receiver.

I. Iridium's Criticisms of Ligado's Technical Analysis Rely on an Inappropriate Propagation Model, Misuse the WG-1 Report's Analysis, and Fail to Use Industry Accepted Losses.

A. Iridium's Propagation Model is Inapplicable to the Basic Parameters Under Review

Iridium's propagation analysis is fundamentally flawed. Specifically, Iridium:

- erroneously uses the Hata-Okumura model for base station heights, separation distances and frequencies that are outside the values for which the model is valid;
- claims, without support, that Iridium's use of the Hata-Okumura model may overestimate real-world propagation loss, and;
- claims that WI-NLOS produces excessive loss, when in fact the WI-NLOS model used by Ligado produces losses equivalent to Iridium's own calculations (using d4), as discussed in part I.B. below.

Iridium's use of the Hata-Okumura propagation model in many of the scenarios analyzed is flawed for a number of reasons.[v]

- The WG-1 scenarios and Ligado-Iridium use case scenarios are substantially different
    - As shown in Figure 1 below, WG-1 analyzes interference scenarios at long range where the receiving meteorological earth station is physically outside and distant from an operating LTE network. WG-1 chose propagation models suitable to that use case and that do not consider local clutter near the LTE devices.[vi] With separation distances from 1 kilometer to as large as 99 kilometers, propagation models such as the Irregular Terrain Model [ITM, also known as the Longley-Rice model]) were deemed suitable, whereas models considering devices located within building clutter and at shorter separation distances (*i.e.,* less than 20 kilometers) were dismissed by WG-1.[vii]
    - The WG-1 scenario used the ITM model, which considers terrain variations but not clutter. Such a model is appropriate where the interference source is at a great distance from the victim (*i.e.*, source and victim are in different geographic regions) and the transmitted radio waves propagate over mostly uncluttered terrain. In the present scenario, both the Ligado and the Iridium terminals are within 10 kilometers of each other and both are in a cluttered environment. Hence, the use of the ITM model is inappropriate in Iridium's present scenarios.

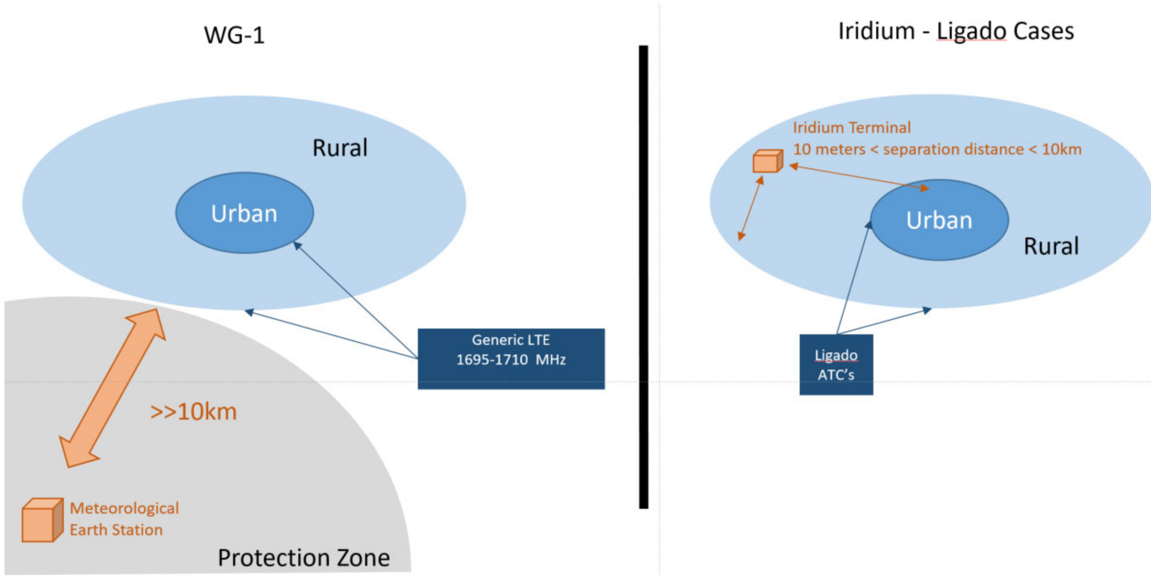

Figure 1

- The use cases raised by Iridium involve separation distances ranging from 10 meters to 10 kilometers. The specific use cases provided by Iridium involve short range considerations where the Iridium and Ligado LTE ATC antennas may be located below rooftop height and may be in the presence of building clutter. The WI-NLOS propagation model supports modeling such use cases.

- The Hata-Okumura model is suited to a variety of conditions not present at ground level.

  - Hata-Okumura is designed for a base station height of 30-200 meters, but Iridium's analysis considers both transmitter and receiver height to be 2 meters, which Iridium itself acknowledges is below the valid Hata-Okumura range.[viii]

  - Hata-Okumura is not only invalid for base station antenna heights below 30 meters, it also is invalid for distances less than 1 kilometer and for the Ligado and Iridium frequencies at issue. Iridium itself admits that Hata-Okumura is invalid for base station antenna heights lower than 30 meters.[ix]

  - It is a well understood physical characteristic that lowering antenna heights will increase propagation loss, which Iridium acknowledges.[x] Importantly, Iridium provides no support for its bare assertion that its use of the model is nonetheless acceptable because the model "may actually overestimate the amount of actual path loss" at lower heights.[xi]

- Because Hata-Okumura is expressly not validated for base station antenna heights lower than 30 meters, it is not possible to make any reliable predictions about how the path loss calculated by the model under such conditions compares to the path loss that would be experienced in the real world.

- Similarly, even though Hata-Okumura is designed for distances of 1-20 kilometers, Iridium improperly extrapolates losses in the range of 100-1000 meters by combining Hata-Okumura and Free-Space Path Loss models. Moreover, Hata-Okumura applies to frequencies in the range of 150-1500 MHz, yet Iridium attempts to use the model to predict path loss at 1626.5 MHz. Again, because the model is not designed for use under these conditions, the resulting path loss claims cannot be considered reliable

- **[BEGIN CONFIDENTIAL]**Ligado recognizes that there have been adaptations to the Hata-Okumura model by Cost-231 where the Cost-231 Hata model is valid for frequencies above 1500 MHz.[xii] "At 1.5-2.0 GHz, it was found by a European study committee (COST231) that the Hata model consistently underestimates path loss and an 'extended Hata model' was developed to correct the situation". While Iridium did not stipulate the Cost-231 Hata, the Cost-231 Hata model is still invalid for base station antenna heights below 30 meters and separation distances less than 1 kilometer. As such, Iridium's September 1, 2016 analysis in section 3.1.4, Figure 2, Table 4, Table 6,[redacted] are invalid. **[END CONFIDENTIAL]**

By contrast to Iridium's reliance on a fundamentally flawed model, Ligado's analysis instead uses the Walfisch-Ikegami model for distances greater than 20 meters where path loss exceeds free-space conditions.[xiii] The Commission recognizes the Walfisch-Ikegami non-line-of-sight ("WI-NLOS") model as an appropriate method for estimating real-world losses for the short range of separation considered in Iridium's use cases.[xiv] As the Commission stated, signals being sent from a transmitter to a receiver may experience any number of disruptions due to their particular path such as reflections off large objects (*e.g.*, buildings), diffraction around or over objects, and scattering due to impinging on smaller objects.[xv] The WI-NLOS model accounts for these factors and is based on measured data and empirical formulation.

WI-NLOS is also feasible to use under conditions where the transmitting and receiving antenna heights are close to the ground as depicted in the Iridium analysis. Iridium's use case considers transmitter and receiver heights of 2 meters each. WI-NLOS is valid for base station heights as low as 4 meters and endpoint heights of 2 meters.

For these reasons, WI-NLOS is the appropriate model for evaluating the real-world path loss experienced by Ligado's proposed ATC devices over distances greater than 20 meters from Iridium mobile terminals, which accounts for three of the four distances Iridium analyzes.

Ligado used this approach in calculating the analysis shown in Table 2 below.[xvi] Ligado's WI-NLOS equations are taken from the National Institute of Standards and Technology ("NIST").[xvii] The WI-NLOS model is valid for base station heights between 4 meters and 50 meters. Accordingly, to most closely approximate the effect of Ligado's devices, which generally will be close to the ground, this analysis considers the Base Station Height (h_b) of 4 meters and Mobile Station Height (h_m) of 2 meters.[xviii] Notably, WI-NLOS can be used to calculate precise values for antenna heights as low as 4 meters and considers the placement of antennas within building clutter at heights below rooftops. As discussed above, using WI-NLOS providers a more accurate calculation of path loss than other models that do not allow for building clutter and antenna placement as close to ground level.

B. Iridium's Use of Propagation Models Analyzing Compatibility With Globalstar in Other Proceedings Supports Ligado's Analysis

Iridium relied on path loss models other than free space in prior submissions to the Commission. For example, Iridium's 2014 Supplemental Comments in the Globalstar proceeding were devoted to the issues associated with expanded spectrum sharing between Iridium and Globalstar.[xix] In Exhibit 2, Table 1 of the Iridium 2014 Supplemental Comments, Iridium analyzes a Globalstar handset's interference to an Iridium handset (subscriber terminal). For the analysis at a separation distance of 100 meters Iridium identified Ground Wave Propagation Loss ("d^4 loss"), which is greater than free-space path loss. <u>Additionally, at 100 meters, the Iridium path loss value of 91.3 dB aligns closely with Ligado's WI-NLOS calculation of 90.5 dB.</u>[xx]

C. Iridium's Reliance on WG-1's Analysis Is Misplaced Because That Analysis Focused on Different Bands and Different Use Cases

Iridium suggests that the WG-1 Report supports its propagation analysis, as well as Iridium's decision to disregard antenna polarization mismatch loss, head/body obstruction loss, building attenuation, and power control reductions.[xxi] To the contrary, however, the WG-1 Report provides no support for Iridium's assumptions because WG-1's interference analysis was based on an entirely different use case. WG-1's task was to "develop a deeper understanding of the issues and options available for maximizing access to the spectrum for commercial services while protecting incumbent federal operations in the 1695-1710 MHz and the adjacent 1675-1695 MHz bands."[xxii] Its analysis thus focused on the potential effect—primarily co-channel interference—of general LTE operations on federal meteorological fixed earth stations. As the Commission understands, co-channel spectrum sharing requires more protection than non-shared spectrum operations in adjacent bands. The assumptions facilitating WG-1's analysis are not applicable to the use case now at issue: the effect of Ligado's specific proposed ATC devices on Iridium terminals operating in adjacent spectrum at 1626.5 MHz.

[BEGIN CONFIDENTIAL] Similarly, the WG-1 Report offers no basis for Iridium's decision to disregard antenna polarization mismatch loss. Unlike the WG-1's analysis, which considered the effect of generic LTE operations, the Iridium-Ligado case requires consideration of the specific antennas used for each terminal (CP - Circular Polarization for Iridium, LP - Linear Polarization for Ligado ATC). Referring to the mobile earth-station terminals use case in Table 1, removing 17 dB of additional antenna discrimination losses further increases the negative margin currently experienced by Iridium to [redacted] from Ligado METs in the FSPL 100 meter case. Moreover, comparing Table 1 and Table 2, one finds that Ligado METs provide for [redacted] more interference than Ligado's proposed ATC terminals.

Table 1

Ligado MET (Upper Limit) - Iridium Real-World Interference Model

Frequency	1626.5	MHz	Med City				
	FSPL	FSPL	WI-NLOS	WI-NLOS	FSPL	FSPL	
MET OOBE Upper Limit	-38.00	-38.00	-38.00	-38.00	-38.00	-38.00	dBW/30 kHz
Separation Distance	10	100	100	1000	1000	4000	Meters
Path Loss	56.7	76.7	90.5	146.6	96.7	108.7	dB
Iridium Reference RX antenna Gain at horizon	-3	-3	-3	-3	-3	-3	dBi
Additional Antenna discrimination between terminals	-17	-17	-17	-17	-17	-17	dB
Received interference power density	[redacted]						dBW/30 kHz
Iridium user terminal noise floor	-154.8	-154.8	-154.8	-154.8	-154.8	-154.8	dBW/30 kHz
I/N	[redacted]						dB
Required I/N	-6	-6	-6	-6	-6	-6	dB
Iridium Margin	[redacted]						dB

Table 2

Ligado LTE ATC - Iridium Real-World Interference Model

Frequency	1626.5	MHz	Med City				
	FSPL	FSPL	WI-NLOS	WI-NLOS	FSPL	FSPL	
Ligado User Terminal OOBE limit	-49.20	-49.20	-49.20	-49.20	-49.20	-49.20	dBW/30 kHz
Separation Distance	10	100	100	1000	1000	4000	Meters
Path Loss	56.7	76.7	90.5	146.6	96.7	108.7	dB
Iridium Reference RX antenna Gain at horizon	-3	-3	-3	-3	-3	-3	dBi
Additional Antenna discrimination between terminals	-17	-17	-17	-17	-17	-17	dB
Received interference power density	[redacted]						dBW/30 kHz
Iridium user terminal noise floor	-154.8	-154.8	-154.8	-154.8	-154.8	-154.8	dBW/30 kHz
I/N	[redacted]						dB
Required I/N	-6	-6	-6	-6	-6	-6	dB
Iridium Margin	[redacted]						dB

[END CONFIDENTIAL]

Attached to this paper as Exhibit 1 is an MSV white paper describing a model for calculating isolation between a CP antenna (Iridium terminal antenna) and a LP antenna (ATC terminal antenna). Iridium asserts that after applying antenna discrimination, the 3 dB for polarization mismatch does not apply.[xxiii] Iridium is incorrect. In analyzing the linearly polarized (LP) ATC antenna and circularly polarized (CP) antenna, one finds that the average polarization mismatch is 3 dB.[xxiv]

In 2002, MSV analyzed polarization mismatch between two terminals similar to the Ligado Iridium case discussed here. The model described in the MSV white paper consists of 2 antennas:

- An LP antenna pointed directly toward the CP antenna.
- A low gain CP antenna (GPS antenna per the FAA compatibility study 10/3/2014)[xxv], whose V-pol and H-pol gain patterns are defined as a function of offset angle from boresight. The CP antenna is pointed toward the LP antenna with a pointing offset relative to boresight of φ, where $0 \le \varphi \le 90°$.

The polarization orientation of the LP antenna relative to the CP antenna major axis is varied in steps from 0 (V-pol) to 90° (H-pol). The results show that, for any CP antenna pointing offset φ, the mismatch loss averaged over all LP antenna orientations Θ from V-pol to H-pol is always 3 dB. Even though this calculation provides support for a 3 dB polarization mismatch, Ligado takes a more conservative approach and utilizes the FCC accepted value of 2 dB in its calculations.[xxvi]

D. Iridium Contradicts Its Own Methodology Regarding In-building Usage Losses

Moreover, Iridium contradicts its own methodology within different portions of the December 14 Technical Response. For instance, in denying consideration of in-building attenuation Iridium asserts that its “decision to exclude in-building Ligado usage is perfectly consistent with WG-1’s methodology, which deliberately excluded any in-building interference scenarios.”[xxvii] Yet at the same time, Iridium’s accompanying analysis of aviation use cases accounts for 20 dB in-building structure losses in its discussion of the effect of “Ligado terminals within an airport terminal near the gate at which an Iridium equipped aircraft is parked.”[xxviii]

Iridium’s analysis is thus flawed because it erroneously applies WG-1 findings to the Iridium-Ligado case, and its own filing contradicts itself on the applicability of in-building losses. The valid part of Iridium’s analysis correctly accounts for in-building structure losses.

E. Iridium Incorrectly Dismisses Antenna Pattern Discrimination, Polarization Mismatch and Head/Body Obstruction Losses

Iridium claims that industry accepted factors should be dismissed from the interference analysis. The Technical Paper states:

- No additional antenna gain pattern discrimination is appropriate and that antenna gain for the Ligado user terminal is accounted for in the EIRP mask.

- Iridium assumed no polarization mismatch loss in its analysis.

- Iridium did not take into account additional signal losses resulting from user head and body obstruction.

As discussed previously, WG-1 considered the aggregate interference from a distant group of LTE terminals that is distinctly different from analyzing mobile devices in close relative proximity as introduced by Iridium. Unlike propagation path loss models, which factor the signal loss propagating between two reference antennas, antenna discrimination considers the local antenna implementation conditions, including orientation and near field losses associated with the device, as well as user and mounting position of the user terminal. While Iridium includes Iridium Reference RX antenna gain at horizon of -3 dBi, it fails to include other implementation factors that cause further signal losses common to the devices provided by Iridium and LTE devices proposed by Ligado. In particular, the Commission has recognized that the combined effect (considering both the transmitting and receiving antenna) of LTE antenna gain, body loss, and polarization mismatch causes a total of 20 dB in signal loss.[xxix] As such, any comprehensive analysis should include an additional 17 dB loss to account for discrimination between terminals (in addition to the -3 dBi included in Iridium's initial calculation).

References

FCC 15-99

	TX	RX	Total		
LTE Antenna Gain	-6	-6	-12	dBi	Paragraph 122
Body Loss	3	3	6	dB	Paragraph 123
Polarization Mismatch (loss)	2		2	dB	Paragraph 124
Additional Antenna discrimination between terminals			**-20**	dB	

FCC 12-151

	TX	RX	Total		
Combined antenna gain and head/body loss	-10	-10	**-20**	dB	Paragraph 142

Figure 2: Antenna Discrimination Between Terminals

II. Ligado's Proposed ATC Operations Are Compatible with Iridium's Newly Presented Aviation Use Cases

Iridium's December 14, 2016 filing discusses the purported impact of Ligado's proposed operations on Iridium's aviation-related services. This paper considers those factors and demonstrates that Ligado's proposal, as revised to specifically address Iridium's concerns, will not cause harm to Iridium's devices.

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A. Ligado Has Proposed a Further [redacted] Reduction in OOBE

In its November 2, 2016 filing, Ligado proposed a further [redacted] reduction in OOBE in the adjacent band to accommodate Iridium's concerns. Ligado proposed that reduction after evaluating the OOBE performance of its proposed LTE devices in light of ongoing technology advances. Ligado thus proposes that in addition to the current OOBE limit of 49.2 dBW / 30 kHz performance an additional [redacted] reduction in OOBE is possible. As such, Ligado would provide interference margin calculations considering OOBE values revised to [redacted] as shown in Figure 3 below.

[redacted]

Figure 3

[END CONFIDENTIAL]

B. Specific Issues Raised by Iridium

1. <u>Polarization Mismatch</u>

For the reasons discussed in Section I.C above, the average polarization mismatch between the linearly polarized (LP) Ligado ATC antenna and the circularly polarized (CP) Iridium antenna is 3 dB. Nonetheless, as stated above in Section 1.E.

Figure 2 and in Ligado's prior filing, Ligado used the Commission's accepted value of 2 dB.

2. Fuselage Blockage

With the Iridium antenna mounted on top of the aircraft to achieve connectivity with overhead satellites, Ligado terminals nearest the airborne craft will be below and obstructed by the fuselage itself. These implementation losses due to incidence angle and fuselage blockage are not considered in Iridium's analysis and would further improve Iridium's margin. Mobile Satellite Ventures in their recent September 2 filing stated that signals originating 30-degrees below the aircraft are subject to 10 dB attenuation.[xxx] Moreover, ECC Report 233 found that aircraft fuselage attenuation is calculated to be 5 dB,[xxxi] and "for signals originating from the ground signal blockage due to the fuselage could be expected since the aircraft satellite antenna will be installed on the top of the aircraft".[xxxii] For the purposes of the present analysis, Ligado applies 6 dB loss due to fuselage blocking in the airborne use cases.

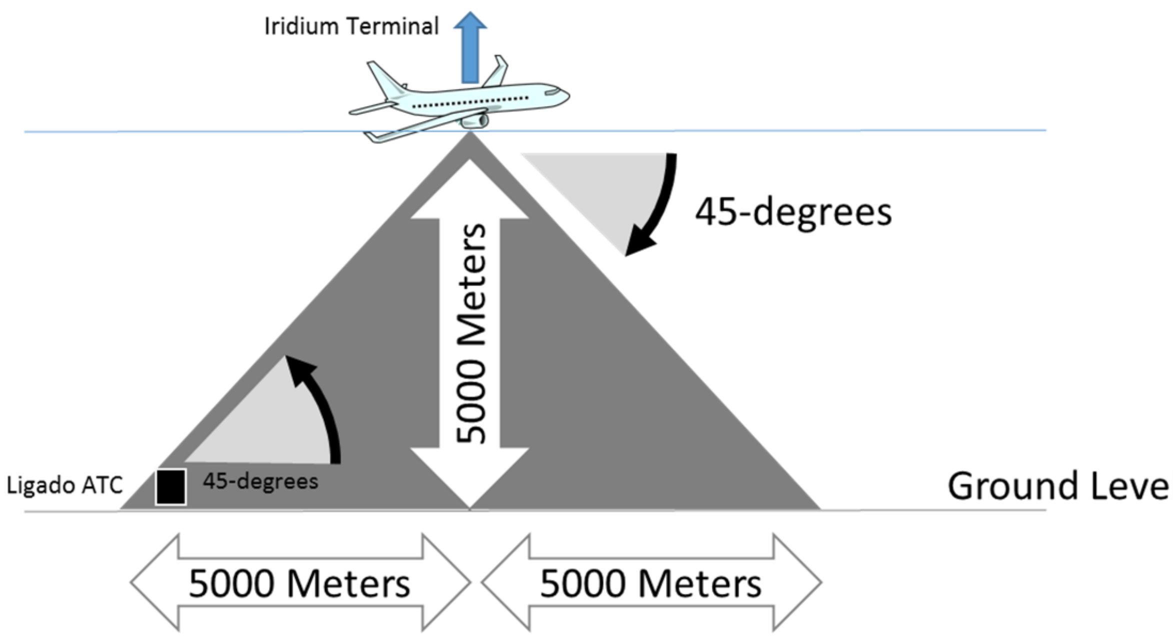

Figure 4

3. Ligado Devices Located Below Horizon

Moreover, these nearby Ligado terminals are positioned relative to the Iridium terminal so they are located at an angle below the horizon and are subject to additional Iridium antenna pattern discrimination where their contributions to the aggregate interference would be reduced and therefore increase the weighted average path loss. Iridium states their receiver antenna gain at the horizon is -6 dBi indicating that antenna gain is decreasing towards the ground (i.e. below the horizon), as is typical for L-band satcom antennas. As shown in Figure 4, for aircraft at 5,000 meters altitude the Ligado devices within 5 km horizontal separation are at least 45-degrees below the horizon as shown in the figure below. Similarly, at 500 meters altitude devices within 1 kilometer separation distance are more than 26-degrees below the horizon. Utilizing a typical quadrifilar helix antenna and the example described in this section, the antenna gain at -45-degrees relative to the horizon is seen to be approximately -12 dBi. Relative to Iridium's baseline of -6 dBi antenna gain towards horizon, Ligado applies 6 dB additional isolation to signals originating in the shaded area described in Figure 4. Due to the lower geometric spreading loss and less clutter in the shaded area of Figure 4 relative to the area outside, the emitters outside the shaded area make less contribution to the aggregate weighted average path loss, in spite of the antenna gain being higher than -12 dBi. Considering contributions from all emitters, in the aggregate, Ligado applies 4 dB additional isolation (instead of 6 dB that would apply in the shaded area of the diagram) to the weighted average path loss. This 4 dB additional isolation (-10 dBi) is additive to the fuselage loss of 6 dB and the Ligado ATC antenna discrimination.

4. OOBE Correction Based on Tabulated CDF Data

Iridium's assessment of the aggregate interference use case (set forth in Tables 2 and 3 of the December 14 Aviation Analysis) is flawed because it fails to account for critical real-world factors governing the use of Ligado's proposed LTE devices.

In this regard, the WG-1 Report provides helpful guidance regarding the appropriate assumptions for LTE uplink operations. As explained in Section I.C above, the WG-1 Report's interference analysis relies on certain assumptions that are not applicable to the Ligado-Iridium use case (such as radio frequency and distance from the transmitting device). However, other aspects of the WG-1 report, such as the power distribution of transmitting devices, are eminently applicable as they are not sensitive to the above parameters. As the WG-1 Report notes, the report "represents a collaborative effort between industry and government representative experts to agree on LTE parameters that are closer to realistic operational parameters than have been used in past analysis."[xxxiii] This paper accordingly uses the Tabulated CDF Data of an LTE system as described in Appendix 3 to the WG-1 Report to model the equipment transmit characteristics power profile. In addition, as will be described later, in analyzing the aggregate interference of Iridium's airborne use case this paper introduces specific factors, including, polarization mismatch and implementation losses specific to Ligado's and Iridium's devices. Such factors were not considered in WG-1's general analysis of fixed meteorological ground stations.

While Iridium's single ATC terminal analysis considers the potential margin under a worst case scenario with a single ATC terminal operating at full power, the WG-1 Report shows that multiple users will in fact operate with a wide distribution of individual transmit power. In Iridium's aggregate analysis of geographically dispersed users, the power distribution must be applied. Appendix 3 of the WG-1 Report provides the distribution of transmit power in a group of terminals. According to WG-1, a sound analysis of the interference environment should consider the following:

a. Use UEs per sector (*i.e.*, the number of simultaneously transmitting UEs) is 6 per transmission time interval (TTI) per sector or 18 per LTE base station, for a 10 MHz Channel.

b. 100 % of uplink resources (PRBs) are *equally distributed among transmitting UEs* in each sector.

c. Randomly assign power in accordance with UE power CDF for each independent Monte-Carlo analysis trial.

In other words, multiple users each transmit on a subset of the channel resources. Moreover, the power of each user must be considered based on the distribution of power according to the Tabulated CDF Data.

In a real world network deployment, LTE UEs do not transmit at full power all of the time. Using power control techniques, the UE uplink transmit power is adjusted in steps to maintain the minimum required link margin based on a UE's path loss from its serving eNodeB among other factors. In fact, power control techniques are not just means of extending UE battery life, but through the constant adjustment of uplink transmit power are also an active form of interference control.

In Appendix 3 of the WG-1 Report, reproduced below, a UE uplink transmit power distribution is provided based on Monte Carlo simulations using the same assumptions referenced in Iridium's analysis, including the number of UEs per eNodeB and eNodeB inter-site distance (and thus the UE density derived therefrom). Using the tabulated power distribution data, the mean UE uplink transmit power is calculated to be +5.52 dBm for the urban/suburban environment and +13.44 dBm for the rural environment. Respectively, these are differences of -14.48 dB and -6.56 dB from the maximum UE transmit EIRP of +20 dBm used in the simulations. It reasonably follows that any OOBE for the purposes of real world interference analysis can be reduced by similar amounts.

Source: CSMAC WG-1 Report, Appendix 3, Tabulated CDF Data

	Urban/Suburban (1.732 Km ISD) (6 UE scheduled/TTI/sector)		Rural (7 Km ISD) (6 UE scheduled/TTI/sector)	
UE EiRP (dBm)	PDF	CDF	PDF	CDF
-40	0	0	0	0
-37	0.0001	0.0001	0	0
-34	0.0002	0.0003	0	0
-31	0.0008	0.0011	0	0
-28	0.002	0.0031	0	0
-25	0.004	0.0071	0	0
-22	0.0083	0.0154	0.0002	0.0002
-19	0.0166	0.032	0.0004	0.0006
-16	0.0327	0.0647	0.0007	0.0013
-13	0.0547	0.1194	0.0026	0.0039
-10	0.0839	0.2033	0.006	0.0099
-7	0.1128	0.316	0.0153	0.0252
-4	0.137	0.453	0.0325	0.0577
-1	0.1429	0.5959	0.0575	0.1152
2	0.1338	0.7297	0.0911	0.2062
5	0.1094	0.839	0.1245	0.3307
8	0.0753	0.9143	0.1536	0.4843
11	0.045	0.9594	0.1605	0.6448
14	0.0236	0.983	0.1473	0.792
17	0.0106	0.9936	0.1203	0.9123
20	0.0064	1	0.0877	1

UE EiRP (Watts)	Weighted Power, Watts (Ur/Sub)	Weighted Power, Watts (Rural)
0.0000001	0.0000000	0.0000000
0.0000002	0.0000000	0.0000000
0.0000004	0.0000000	0.0000000
0.0000008	0.0000000	0.0000000
0.0000016	0.0000000	0.0000000
0.0000032	0.0000000	0.0000000
0.0000063	0.0000001	0.0000000
0.0000126	0.0000002	0.0000000
0.0000251	0.0000008	0.0000000
0.0000501	0.0000027	0.0000001
0.0001000	0.0000084	0.0000006
0.0001995	0.0000225	0.0000031
0.0003981	0.0000545	0.0000129
0.0007943	0.0001135	0.0000457
0.0015849	0.0002121	0.0001444
0.0031623	0.0003460	0.0003937
0.0063096	0.0004751	0.0009692
0.0125893	0.0005665	0.0020206
0.0251189	0.0005928	0.0037000
0.0501187	0.0005313	0.0060293
0.1000000	0.0006400	0.0087700

Mean UE EiRP (Watts)	**0.0035665**	**0.0220895**
Mean UE EiRP (dBm)	**5.52**	**13.44**
Percentile	**84.7%**	**75.5%**

Max UE EiRP (dBm)	**20**	**20**
EiRP Delta (dB)	**-14.48**	**-6.56**

Figure 5

Furthermore, an LTE UE's uplink transmission does not fully occupy the entire channel bandwidth at any point in time. Rather, a determination by the resource scheduler assigns the UE a subset of available Physical Resource Blocks (PRBs). In essence, a PRB is a 180 kHz block of subcarriers in the frequency domain. Visualizing the characteristic sloped roll-off shape of a typical transmission mask, it is reasonable then to expect any OOBE in the Big LEO band will vary depending on whether a UE is assigned PRBs towards the lower end of the Lower 10 MHz channel versus PRBs towards the upper end of the Lower 10 MHz channel. Thus, it is not reasonable to consider OOBE from multiple UEs in the Lower 10 MHz channel as additive with equal weight. For PRBs offset from the channel, there will be further improvements in Iridium margin; however, such improvements are not factored into this analysis.

OOBE emissions are closely correlated to the fundamental transmit power of the transmitter and a reduction in power also reduces OOBE. Discussions within CSMAC WG-1 concluded that with a decrease in fundamental transmit power there is one dB for one dB reduction in OOBE. As such, a dB for dB reduction will be applied to OOBE values according to the Tabulated CDF Data.

[BEGIN CONFIDENTIAL] As shown in the tables below, factoring appropriate propagation models, polarization mismatch, fuselage blockage, and OOBE correction according to the tabulated CDF across a pool of devices there is more than [redacted] margin across the various aircraft Take Off/Landing and Helicopter Aggregate Interference results for both high and low density scenarios.

Table 3

Low Altitude Aircraft Take Off/Landing and Helicopter Aggregate Interference Results (Low Density Ligado User Terminals)

Ligado User OOBE Limit	[redacted]						dBw/30kHz
Frequency	1626.5	1626.5	1626.5	1626.5	1626.5	1626.5	MHz
Interference Radius	1	5	10	1	5	10	km
Ligado Users Per Cell	18	18	18	18	18	18	
Ligado cell Radius	3.5	3.5	3.5	3.5	3.5	3.5	km
Number of Users within Cell Radius	1.5	36.7	146.9	1.5	36.7	146.9	
Aircraft Height	100.00	100.00	100.00	500.00	500.00	500.00	m
Weighted Average Path Loss	[redacted]						dB
Iridium receiver antena gan at horizon	-6.0	-6.0	-6.0	-6.0	-6.0	-6.0	dBi
Polarization mismatch	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	dB
Fuselage blocking loss	6.0	6.0	6.0	6.0	6.0	6.0	dB
Ligado ATC antenna discrimination toward Iridium receiver	-6.0	-6.0	-6.0	-6.0	-6.0	-6.0	dB
Additional Iridium antenna discrimination below horizon	-4.0	-4.0	-4.0	-4.0	-4.0	-4.0	dB
OOBE correction based on CDF	-6.6	-6.6	-6.6	-6.6	-6.6	-6.6	dB
Aggregate Receive Interference Power Density	[redacted]						dBw/30kHz
Iridium User Terminal Noise Floor	-154.8	-154.8	-154.8	-154.8	-154.8	-154.8	dBw/30kHz
I/N	[redacted]						dB
Required I/N	-6.0	-6.0	-6.0	-6.0	-6.0	-6.0	dB
Margin	[redacted]						dB

Table 4

Low Altitude Aircraft Take Off/Landing and Helicopter Aggregate Interference Results (High Density Ligado User Terminals)

Ligado User OOBE Limit	[redacted]						dBw/30kHz
Frequency	1626.5	1626.5	1626.5	1626.5	1626.5	1626.5	MHz
Interference Radius	1	5	10	1	5	10	km
Ligado Users Per Cell	18	18	18	18	18	18	
Ligado cell Radius	1	1	1	1	1	1	km
Number of Users within Cell Radius	18.0	450.0	1800.0	18.0	450.0	1800.0	
Aircraft Height	100.00	100.00	100.00	500.00	500.00	500.00	m
Weighted Average Path Loss	[redacted]						dB
Iridium receiver antenna gain at horizon	-6.0	-6.0	-6.0	-6.0	-6.0	-6.0	dBi
Polarization mismatch	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	dB
Fuselage blocking loss	6.0	6.0	6.0	6.0	6.0	6.0	dB
Ligado ATC antenna discrimination toward Iridium receiver	-6.0	-6.0	-6.0	-6.0	-6.0	-6.0	dB

Additional Iridium antenna discrimination below horizon	-4.0	-4.0	-4.0	-4.0	-4.0	-4.0	dB
OOBE correction based on CDF	-14.5	-14.5	-14.5	-14.5	-14.5	-14.5	dB
Aggregate Receive Interference Power Density	[redacted]						dBw/30kHz
Iridium User Terminal Noise Floor	-154.8	-154.8	-154.8	-154.8	-154.8	-154.8	dBw/30kHz
I/N	[redacted]						dB
Required I/N	-6.0	-6.0	-6.0	-6.0	-6.0	-6.0	dB
Margin	[redacted]						dB

Considering the airborne scenario where the aircraft is at an altitude of 5,000 meters and factoring in the polarization mismatch, fuselage blockage, and OOBE correction according to the tabulated CDF across a pool of devices there is more than [redacted] margin across the various aircraft Take Off/Landing and Helicopter Aggregate Interference results for both high and low density scenarios. **[END CONFIDENTIAL]**

For the purposes of this analysis Ligado is not altering the path loss values Iridium presented in its tables. Ligado notes, however, that the values Iridium presents rely on calculations under the Hata-Okumura model under conditions (such as distances less than 1 kilometer, frequency ranges and heights) for which Hata-Okumura is invalid, for the reasons described above.[xxxiv] For clarity, Ligado's inclusion of Iridium's path loss values in the tables below should not be construed as a concession that these values are accurate.

[BEGIN CONFIDENTIAL]

Table 5

Medium Altitude Aircraft Take Off/Landing and Helicopter Aggregate Interference Results (Low Density Ligado User Terminals)

Ligado User OOBE Limit	[redacted]		dBw/30kHz
Frequency	1626.5	1626.5	MHz
Interference Radius	5	10	km
Ligado Users Per Cell	18	18	
Ligado cell Radius	3.5	3.5	km
Number of Users within Cell Radius	36.7	146.9	
Aircraft Height	5000.00	5000.00	m
Weighted Average Path Loss	[redacted]		dB
Iridium receiver antenna gain at horizon	-6.0	-6.0	dBi
Polarization mismatch	-2.0	-2.0	dB
Fuselage blocking loss	6.0	6.0	dB
Ligado ATC antenna discrimination toward Iridium receiver	-6.0	-6.0	dB
Additional Iridium antenna discrimination below horizon	-4.0	-4.0	dB
OOBE correction based on CDF	-6.6	-6.6	dB
Aggregate Receive Interference Power Density	[redacted]		dBw/30kHz

Iridium User Terminal Noise Floor	-154.8	-154.8	dBw/30kHz
I/N	[redacted]		dB
Required I/N	-6.0	-6.0	dB
Margin	[redacted]		dB

Table 6

Medium Altitude Aircraft Take Off/Landing and Helicopter Aggregate Interference Results (High Density Ligado User Terminals)

Ligado User OOBE Limit	[redacted]		dBw/30kHz
Frequency	1626.5	1626.5	MHz
Interference Radius	5	10	km
Ligado Users Per Cell	18	18	
Ligado cell Radius	1	1	km
Number of Users within Cell Radius	450.0	1800.0	
Aircraft Height	5000.00	5000.00	m
Weighted Average Path Loss	[redacted]		dB
Iridium receiver antenna gain at horizon	-6.0	-6.0	dBi
Polarization mismatch	-2.0	-2.0	dB
Fuselage blocking loss	6.0	6.0	dB
Ligado ATC antenna discrimination toward Iridium receiver	-6.0	-6.0	dB
Additional Iridium antenna discrimination below horizon	-4.0	-4.0	dB
OOBE correction based on CDF	-14.5	-14.5	dB
Aggregate Receive Interference Power Density	[redacted]		dBw/30kHz
Iridium User Terminal Noise Floor	-154.8	-154.8	dBw/30kHz
I/N	[redacted]		dB
Required I/N	-6.0	-6.0	dB
Margin	[redacted]		dB

[END CONFIDENTIAL]

5. Same Aircraft

In the case where Iridium and Ligado terminals are co-located on the same aircraft, the two parties can confer and coordinate to minimize interference between terminals. The need to be aware of and manage the use of more than one terminal on an aircraft is not without precedent as RTCA recommends caution to owners, operators and installers that simultaneous independent operation of both Inmarsat and Iridium AES terminals on the same aircraft may cause significant interference to all Iridium AMSS and AMS(R)S services.[xxxv]

6. Airport Terminal Gate

In the case where an aircraft is at the terminal gate and a Ligado user is operating inside the terminal, Iridium fails to consider industry accepted factors of 3 dB for body loss, 2 dB polarization mismatch loss, and 6 dB for antenna discrimination towards the Iridium terminal.

Furthermore, as the Commission is well aware, in order to service the needs of all users within its coverage, the LTE base station interleaves users with packets to send through its scheduling function. The LTE uplink scheduling operation performed by the base station can be resolved into per-domain scheduling:

- Time Domain Packet Scheduling (TDPS): In TDPS, the scheduler performs prioritization of the currently active UEs to be scheduled and interleaved for the upcoming transmission time intervals (TTIs) where different LTE terminals are transmitting at different times.

- Frequency Domain Packet Scheduling (FDPS). In FDPS, LTE terminal share a subset of frequency resources.

Considering the cell radius introduced by Iridium (1 km suburban / 3.5 km rural), the Ligado base station coverage in this use case encompasses a significant portion of an airport. It is reasonable to assume that the five Ligado users described in Iridium's Terminal Gate case represent a small portion of users served by the base station. These five users at the terminal gate (as depicted in Figure 6) will be interleaved via TDPS and FDPS with all users served by the LTE base station. It is unlikely, considering the service footprint of the base station and random assignment of resources to users, that the five Terminal Gate users will be instructed to transmit simultaneously (albeit at different subchannel frequencies) by the base station scheduler. Moreover, it is reasonable to assume that one or more of the five users may be transmitting at less than full power. As such, the five user aggregate case is unlikely to produce margin lower than the single user case.

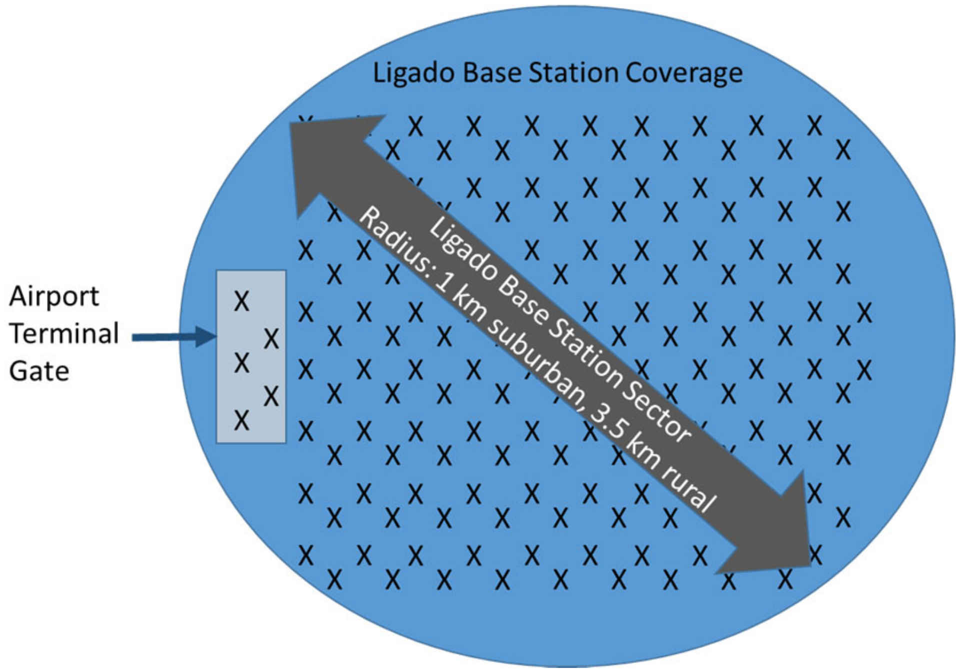

Figure 6

[BEGIN CONFIDENTIAL] The resulting margin in the single and five user scenario is [redacted]

Table 7

Airport Terminal Gate Interference Results

Ligado user terminal OOBE limit	[redacted]		dBW/30kHz
Frequency	1626.5	1626.5	MHz
Separation distance between Ligado user terminal and Iridium-equipped aircraft	100	100	m
Ligado users in airport terminal within 100 m of Iridium-equipped aircraft	1	5	
Free space path loss at 100 m	76.6	76.6	dB
Additional airport structure attenuation	20	20	dB
Iridium receiver antenna gain at horizon	-3	-3	dBi
Ligado transmitter body loss	3	3	dB
Polarization mismatch	2	2	dB
Ligado antenna discrimination toward Iridium receiver	-6	-6	dB
Aggregate received interference power density	[redacted]		dBW/30kHz
Iridium user terminal noise floor	-154.8	-154.8	dBW/30kHz
I/N	[redacted]		dB
Required I/N	-6	-6	dB
Margin	[redacted]		dB

[END CONFIDENTIAL]

III. Iridium’s Model Shows That It Cannot Operate in the Existing Environment It Faces

Finally, Iridium’s claim that Ligado’s proposed terrestrial network would adversely change the environment in which Iridium currently operates fails to take into account the existing regulatory and operational environment Iridium faces today. Ligado seeks to deploy *0.2 watt* user terminals in spectrum adjacent to Iridium. Existing ATC rules, in place for more than a decade, permit the deployment of an unlimited number of *1 watt* user terminals in the L Band,[xxxvi] and require that Iridium’s system be designed to tolerate a level of out-of-band emissions far in excess of what Ligado’s 0.2 watt user terminals would create.[xxxvii]

Iridium’s engineering design team certainly is aware that the Commission already has authorized over *five million* satellite user terminals to operate in L-Band spectrum at much higher power levels than those at which Ligado now proposes to operate.[xxxviii]

More particularly, the authorized satellite user terminals in the adjacent spectrum band on which the Ligado and Inmarsat MSS networks operate could be (and based on publicly available information are) located and used on aircraft, trains, boats, ships, trucks, tractor trailers, cargo containers, or any variety of other vehicles or vessels, or affixed to critical infrastructure; used on a mobile, transportable, or stationary basis; operated in close proximity to Iridium terminals virtually anywhere and at any time; operating with much higher in-band power levels, and producing much higher levels of out-of-band emissions into Iridium’s secondary downlink spectrum, than Ligado’s proposed 0.2 watt user terminals. We are not aware of any evidence, and Iridium has cited none, that the operation of any such authorized satellite user transmitters creates harmful interference into Iridium’s downlink operations, whether those user transmitters are considered individually or in the aggregate.

This existing operating environment raises an important question: If Iridium were to apply the interference model it proposes be used on Ligado’s deployment of 0.2 watt devices to these *already authorized satellite users* of adjacent spectrum, would Iridium’s model show that Iridium is able to operate in the presence of even a single one of these other types of satellite user terminals? The answer is “no.”

By way of example, under Iridium’s model, a helicopter with an Iridium terminal landing near a freeway for a medical emergency would not be able to communicate *if just one tractor trailer* outfitted with an Orbcomm user terminal were nearby and communicating with the Inmarsat MSS network. Similarly under Iridium’s model, a tractor trailer or metro train with an Orbcomm user terminal passing by any major airport would prevent aircraft on the nearby tarmac with an Iridium terminal from properly completing pre-flight checks. The extension of Iridium’s model to these other use cases is illustrated in the attached Exhibit 2. So applying Iridium’s interference model on its own terms, this filing demonstrates that Iridium devices would not be able to operate in a very large zone around other types of authorized satellite user terminals. Specifically, applying Iridium’s own analysis to this use case indicates that Iridium could not operate in a zone with a diameter of *tens of kilometers* around any one of the millions of satellite user terminals operating under the terms of their licenses such as an Orbcomm user terminal. The reason is that these other types of satellite user terminals could produce 2.5 to 10,000 times the in-band power level, and 12 to 15,000 times the out-of-band-emissions level, proposed by Ligado in its license modification applications, and in doing so, those satellite user terminals would fully comply with applicable FCC limits. See Figure 7 below.

Because the use cases involving widespread deployment of mobile earth-station terminals described above are observable every day,[xxxix] it seems obvious that in fact these types of high-powered authorized satellite user terminals do not disrupt Iridium service in areas around any Iridium terminal. And that leads one to further conclude that the Iridium model is unduly conservative and produces grossly inaccurate results. Instead, the Commission should examine the technical analysis presented herein that illustrates how Ligado's proposal improves the nature of the operating environment that Iridium otherwise would have to accept if Ligado's license modification is not granted and presents no realistic threat of harmful interference into Iridium.

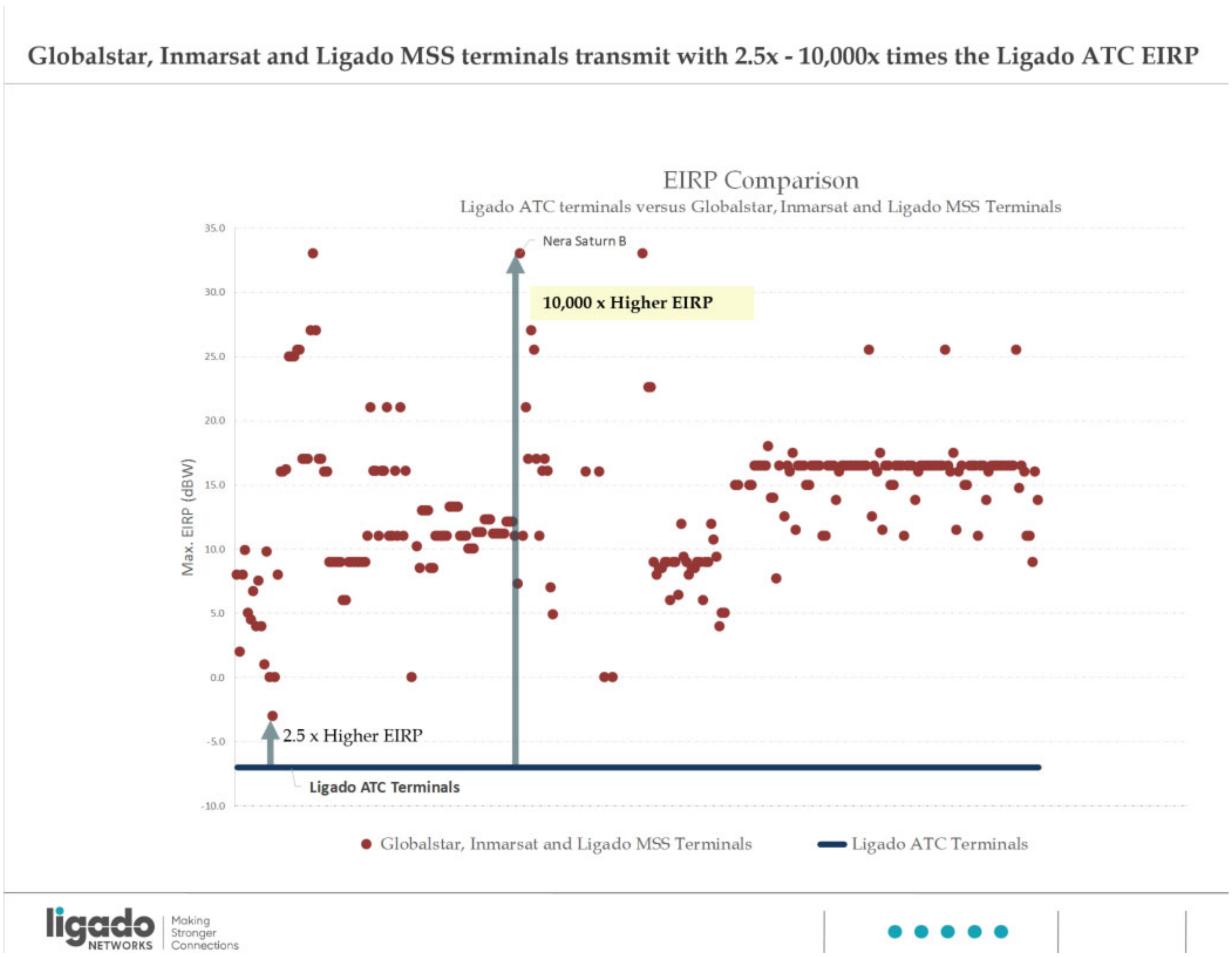

Figure 7

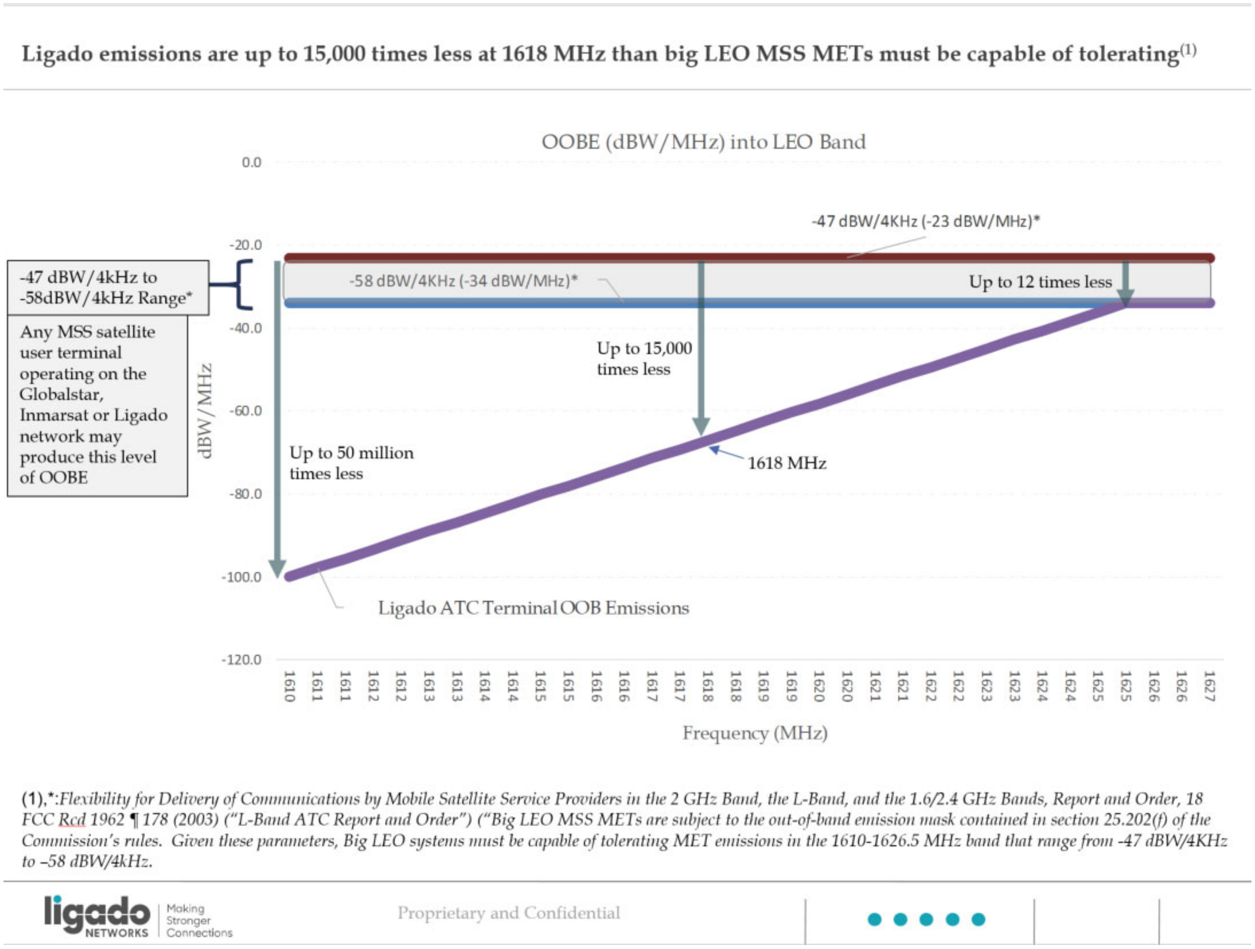

Figure 8

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i Letter from Bryan N. Tramont, counsel for Iridium, to Marlene H. Dortch, FCC Secretary, IB Docket No. 11-109 *et al.* (Dec. 14, 2016) ("December 14 Technical Response")

ii Technical Analysis of Ligado Interference Impact on Iridium Aviation Services, IB Docket No. 11-109 *et al.* (Dec. 14, 2016) ("December 14 Aviation Analysis")

iii *See* Letter from Gerard J. Waldron, counsel for Ligado, to Marlene H. Dortch, FCC Secretary, IB Docket No. 11-109 *et al.* (Nov. 2, 2016) ("Ligado November 2 *ex parte*").

iv Commerce Spectrum Mgmt. Advisory Comm., *Working Group 1 – 1695-1710 MHz Meteorological-Satellite, Final Report*, Rev. 1, at Apps. 3-4 (July 23, 2013), https://www.ntia.doc.gov/files/ntia/publications/wg1_report_07232013.pdf ("WG-1 Report").

v *Id.*; *see also* Masaharu Hata, *Empirical Formula for Propagation Loss in Land Mobile Radio Services*, IEEE Transactions on Vehicular Technology (Aug. 1980).

vi *See* WG-1 Report at Appendix 7 ("The calculated protection distances in Table 6 are based on the assumption that the commercial wireless licensees will design their base stations and network lay down to control the handsets so they will not operate within the [Meteorological Earth Station] protection zones.")

vii *See id*. ("In general it was found that most of these existing propagation models are used for predicting signal strength and propagation path loss for relatively short range paths (i.e.., distances less than 20 km) in built-up urban/suburban areas where there are numerous man-made building structures.")

viii December 14 Technical Response at 2.

ix *Id*. at 2.

x December 14 Technical Response at 3.

xi *Id* at 3.

xii Dieter J. Cichon and Thomas Kurner, *Digital Mobile Radio Towards Future Generation Systems: Cost 231 Final Report*, at ch. 4, http://www.lx.it.pt/cost231/final_report.htm.

xiii *See* National Institute of Standards and Technology, Description of Hata, CCIR, and Walfisch-Ikegami Models, at 6, http://www.itl.nist.gov/div892/wctg/manet/calcmodels_dstlr.pdf.

xiv *Id*.; *Flexibility for Delivery of Communications by Mobile Satellite Service Providers*, Report & Order and Notice of Proposed Rulemaking, 18 FCC Rcd 1962, at App'x C1 § 1.6 (2003).

xv FCC, *Public Safety Tech Topic #17 - Propagation Characterization*, https://www.fcc.gov/help/public-safety-tech-topic-17-propagation-characterizatio.

xvi To be clear, while Ligado shows free space path loss for values greater than 20 meters in order to compare Iridium and Ligado's results, Ligado does not concede that these are valid results for path loss.

xvii *See* National Institute of Standards and Technology, Description of Hata, CCIR, and Walfisch-Ikegami Models, http://www.itl.nist.gov/div892/wctg/manet/calcmodels_dstlr.pdf.

xviii *Id.*

xix *See* Supplemental Comments of Iridium Constellation LLC, RM-11697, RM-11685, IB Docket No. 12-213 (Nov. 5, 2014) ("Iridium 2014 Supplemental Comments").

xx *See* Iridium 2014 Supplemental Comments at Exhibit 2 p. 3.

xxi December 14 Technical Response at 3, 4, 6.

xxii WG-1 Report at 1.

xxiii *See* December 14 Technical Response at 4.

xxiv Polarization Mismatch Loss between Two Elliptically Polarized Antennas, G. Churan, MSV 1/04/02 and spreadsheet per M. Aliani

xxv Polarization Mismatch Loss between Two Elliptically Polarized Antennas, G. Churan, MSV, 1/04/02

xxvi *See Amendment of Part 15 of the Commission's Rules for Unlicensed Operations in the Television Bands, Repurposed 600 MHz Band, 600 MHz Guard Bands and Duplex Gap, and Channel 37*, Report & Order, ET Docket No. 14-165 GN Docket No. 12-268 at ¶124 (2015) ("FCC 15-99").

xxvii December 14 Technical Response at 6.

xxviii December 14 Aviation Analysis at 16-17.

xxix *See Amendment of Part 15 of the Commission's Rules for Unlicensed Operations in the Television Bands, Repurposed 600 MHz Band, 600 MHz Guard Bands and Duplex Gap, and Channel 37*, Report & Order, ET Docket No. 14-165 GN Docket No. 12-268 at ¶¶ 122-124 (2015) ("FCC 15-99"); *Service Rules for Advanced Wireless Services in the 2000-2020 and 2180-2200 MHz Bands*, Report & Order and Order of Proposed Modification, WT Docket No. 12-70 ET Docket No. 10-142 WT Docket No. 04-356 at ¶ 142 (2012) ("FCC 12-151").

xxx Reply of Mobile Satellite Ventures Subsidiary, LLC, IB Docket No. 01-185 (Sept. 2, 2016).

xxxi *See* www.erodocdb.dk/Docs/doc98/official/pdf/ECCREP233.PDF*,* at 21.

xxxii *Id*. at 36.

xxxiii WG-1 Report at App'x 3-2.

xxxiv Hata-Okumura is invalid for 1627.5 MHz. Extended Hata is invalid for heights exceeding 200 m. Both models are invalid for separation distances less than 1 kilometer. http://www.itl.nist.gov/div892/wctg/manet/calcmodels_dstlr.pdf

xxxv Minimum Operational Performance Standards for Avionics Supporting Next Generation Satellite Systems (NGSS), RTCA, DO-262B, Appendix D, 1.3.5.1, at D-27-28 (June 17, 2014)

xxxvi *Flexibility for Delivery of Communications by Mobile Satellite Service Providers in the 2 GHz Band, the L-Band, and the 1.6/2.4 GHz Bands*, Memorandum Opinion and Order and Second Order on Reconsideration, 20 FCC Rcd 4616 ¶ 49, Appendix B at § 25.253(g)(1) (2005) ("*L-Band ATC Second Reconsideration Order*").

xxxvii *Flexibility for Delivery of Communications by Mobile Satellite Service Providers in the 2 GHz Band, the L-Band, and the 1.6/2.4 GHz Bands*, Report and Order, 18 FCC Rcd 1962 ¶ 78 (2003) ("*L-Band ATC Report and Order*") ("Big LEO MSS METs are subject to the out-of-band emission mask contained in section 25.202(f) of the Commission's rules. Given these parameters, Big LEO systems *must be capable of tolerating* MET emissions in the 1610-1626.5 MHz band that range from -47 dBW/4 kHz to –58 dBW/4 kHz. The peak EIRP of MSV's ATC MTs is 0.0 dBW with a bandwidth of 200 kHz. Using the same section 25.202(f) out-of-band emission mask that applies to Big LEO terminals yields a maximum ATC MET emission level of – 60 dBW/4 kHz that could be present in the Big LEO frequency band. Since this value is lower than the more restrictive emission levels that Big LEO METs are permitted to emit in the Big LEO band, *out-of-band emissions from MSV's ATC METs will not interfere with Big LEO systems operating in the adjacent spectrum*.") (emphasis supplied).

xxxviii *See, e.g.*, Licenses for Call Signs E970381 (authorizing Globalstar to operate over 3.5 million mobile earth terminals ("METs"), E130033 (authorizing ViaSat to operate 500,000 METs to communicate with Ligado), E000725 (authorizing SkyBitz to operate 450,000 METs to communicate with Ligado and Inmarsat), E090032 (authorizing Inmarsat to operate 150,000 METs), E100192 (authorizing ORBCOMM to operate 100,000 METs to communicate with Inmarsat), E030120 (authorizing AmTech Systems to operate 100,000 METs to communicate with Ligado and Inmarsat), E930367 (authorizing Ligado to operate 100,000 METs), E980179 (authorizing Ligado to operate 100,000 METs), E030055 (authorizing ORBCOMM to operate 50,000 METs to communicate with Inmarsat), E050276 (authorizing Airbus to operate 40,000 METs to communicate with Inmarsat), E990083 (authorizing National Systems & Research Co. to operate 40,000 METs to communicate with Ligado), E050348 (authorizing USSecurenet to operate 40,000 METs to communicate with Inmarsat), E020074 (authorizing Honeywell International to operate 25,000 METs to communicate with Inmarsat), E090029 (authorizing Comtech to operate 25,000 METs to communicate with Ligado and Inmarsat), E980159 (authorizing Satcom Systems to operate 25,000 METs to communicate with Ligado), E050249 (authorizing Inmarsat to operate 20,000 METs), and E980203 (authorizing OuterLink to operate 20,000 METs to communicate with Ligado).

[xxxix] See, e,g, http://www.orbcomm.com/en/networks/satellite/isatdata-pro; http://www.inmarsat.com/service/isatm2m/; http://www.inmarsat.com/service/isatdata-pro/

Exhibit 1

MSV
Mobile Satellite Ventures LLC

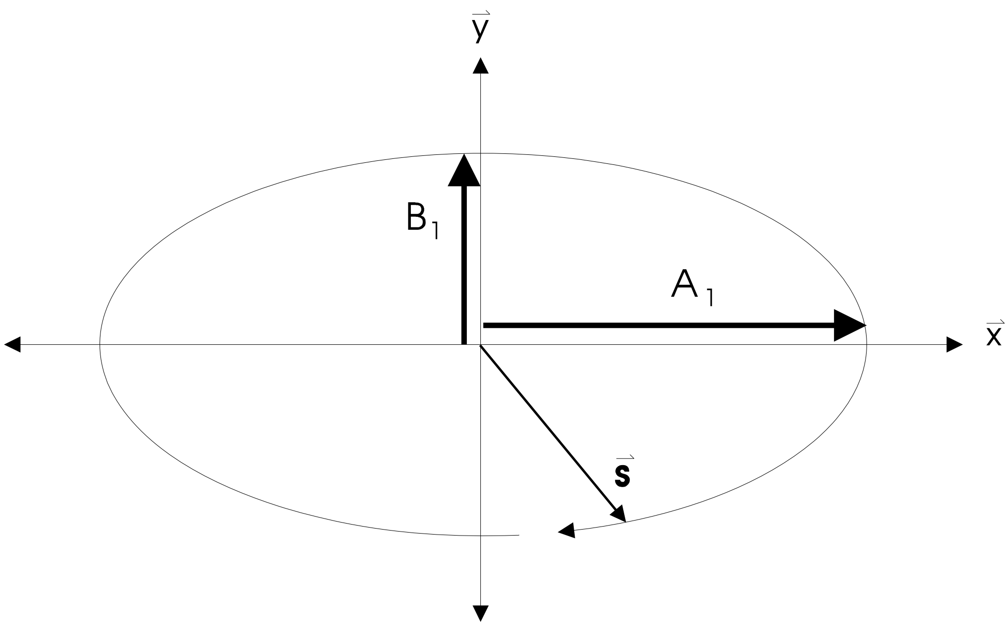
Polarization Mismatch Loss between Two Elliptically Polarized Antennas

G. Churan, MSV
1/04/02

Introduction:
In this paper, a general formula is derived for calculating the polarization mismatch loss (also called coupling efficiency) between two elliptically polarized antennas. The input parameters for the calculation are the axial ratios of the two antennas, the polarization sense, and the angle between the major axes of the two antennas. The formula can be extended to treat linear polarization (by setting the axial ratio to a very large number) or circular polarization (axial ratio =1), which are just limiting cases of elliptical polarization. Following the derivation, polarization mismatch losses are calculated for a few specific cases of interest.

Analysis:
Consider 2 elliptically polarized antennas, denoted antenna #1 and antenna #2, which are defined by their polarization sense and axial ratios r_1 and r_2. Antenna #1 transmits a right-hand circularly polarized c.w. carrier s(t) toward receive antenna #2. The voltage vector of s(t) is depicted in Figure 1, where the direction of propagation is into the page.

Figure 1: Transmitted Signal s(t) From Antenna #1



The voltage vector **s** rotates in a clockwise direction along the ellipse shown in Figure 1. A_1 is the peak magnitude along the major axis (x-axis) and B_1 is the peak magnitude along the minor axis (y-axis). The axial ratio is defined as the ratio of the voltage along the major axis to the voltage along the minor axis. For antenna #1, the axial ratio r_1 is:

$$r_1 = A_1 / B_1 \qquad (1 \le r_1 \le \infty) \tag{1}$$

The signal s(t) can be expressed as the sum of perpendicular vector components along the major and minor axes as follows:

$$s(t) = A_1 \sin(\omega t + \varphi)\underline{\underline{\boldsymbol{x}}} + B_1 \cos(\omega t + \varphi)\underline{\underline{\boldsymbol{y}}} \qquad \text{(right-hand sense)} \tag{2}$$

where ω is the carrier frequency, φ is an arbitrary phase constant, and $\underline{\underline{\boldsymbol{x}}}$ and $\underline{\underline{\boldsymbol{y}}}$ indicate the vector directions along the major and minor axes, respectively.

To facilitate the development that follows, we now require that the time-averaged power of s(t) be equal to 1 for any choice of r_1. Let Ps denote the time-averaged power of s(t). Then:

$$Ps = \lim_{T\to\infty} 1/T \int_{-T/2}^{T/2} s^2(t)\,dt = \lim_{T\to\infty} 1/T \int_{-T/2}^{T/2} \left[A_1^2\sin^2(\omega t+\varphi) + B_1^2\cos^2(\omega t+\varphi)\right] dt$$

$$= \left[A_1^2 + B_1^2\right]/2 = 1. \tag{3}$$

Using equations (1) and (3), the magnitudes A_1 and B_1 can now be expressed in terms of the antenna axial ratio as follows:

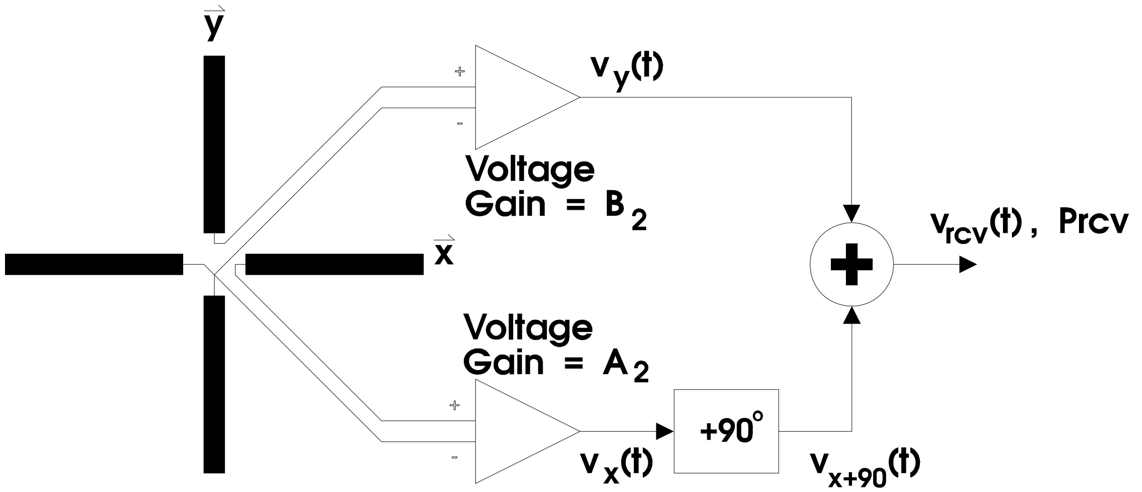
$$A_1 = r_1 \left[2/(r_1^2+1)\right]^{1/2} \tag{4}$$

$$B_1 = \left[2/(r_1^2+1)\right]^{1/2} \tag{5}$$

The elliptically polarized receive antenna #2 is shown in Figure 2. It consists of two identical linearly polarized elements perpendicularly oriented along the major axis (x-axis) and minor axis (y-axis) of the ellipse. The received voltages from the two elements are amplified by gain constants A_2 (major axis) and B_2 (minor axis), to produce output voltage signals $v_x(t)$ and $v_y(t)$, respectively. The signal $v_x(t)$ is then phase shifted by $+90^o$ to produce $v_{x+90}(t)$. The $+90^o$ phase shift gives the antenna a right-hand polarization sense. Finally, the antenna output signal $v_{rcv}(t)$ is given by:

$$v_{rcv}(t) = v_{x+90}(t) + v_y(t). \tag{6}$$

Figure 2: Receive Antenna #2 Block Diagram



The axial ratio r_2 for this antenna is defined by the ratio of the voltage response in the major axis to the voltage response in the minor axis, which are in turn set by the gains A_2 and B_2 , respectively:

$$r_2 = A_2/B_2 \qquad (1 \le r_2 \le \infty) \tag{7}$$

We now impose a second requirement, that the gain of receive antenna #2 remain constant at unity gain regardless of the value selected for r_2. That is, the antenna output signal power (Prcv in Figure 2) must equal the signal input power Ps when the transmit and receive polarizations are identically matched. For this condition to hold, the squared voltage gains for the two orthogonal antenna elements must sum to 1. Thus:

$$\text{Antenna Gain} = A_2^2 + B_2^2 = 1. \tag{8}$$

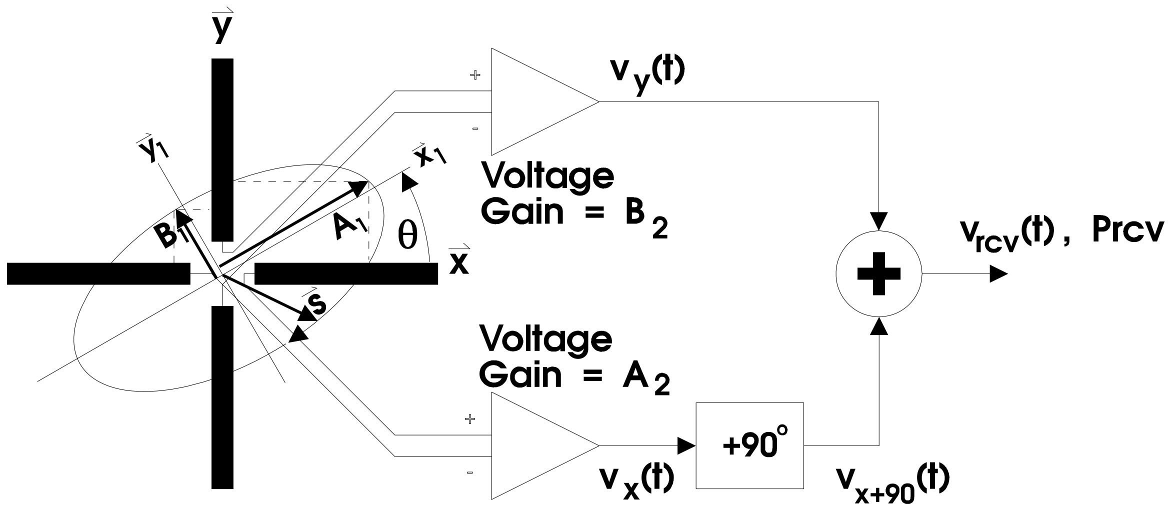
Equations (7) and (8) lead to the following expressions for A_2 and B_2 in terms of antenna axial ratio r_2:

$$A_2 = r_2 / (r_2^2 + 1)^{1/2} \tag{9}$$

$$B_2 = 1/(r_2^2 + 1)^{1/2} \tag{10}$$

Figure 3 illustrates the transmitted signal s(t) voltage vector which is now superimposed on the receive antenna. The angle between the major axes of the transmit and receive antennas is denoted θ.

Figure 3: Transmitted Signal Orientation Relative to Receive Antenna



Recalling the expression for s(t) in equation (2), and given the angle θ between the transmit and receive major axes, the following expressions are derived for $v_x(t)$ and $v_y(t)$:

$$v_x(t) = A_2 \left[A_1 \cos(\theta) \sin(\omega t +\varphi) - B_1 \sin(\theta) \cos(\omega t +\varphi) \right] \tag{11}$$

$$v_y(t) = B_2 \left[A_1 \sin(\theta) \sin(\omega t +\varphi) + B_1 \cos(\theta) \cos(\omega t +\varphi) \right] \tag{12}$$

Phase shifting of $v_x(t)$ by $+90^o$ yields:

$$\begin{aligned} v_{x+90}(t) &= A_2 \left[A_1 \cos(\theta) \sin(\omega t +\varphi +90^o) - B_1 \sin(\theta) \cos(\omega t +\varphi +90^o) \right] \\ &= A_2 \left[A_1 \cos(\theta) \cos(\omega t +\varphi) + B_1 \sin(\theta) \sin(\omega t +\varphi) \right] \end{aligned} \tag{13}$$

Then from equations (12) and (13), the antenna output signal $v_{rcv}(t)$ in Figure 3 is:

$$v_{rcv}(t) = v_{x+90}(t) + v_y(t) = K_C \cos(\omega t +\varphi) + K_S \sin(\omega t +\varphi) \tag{14}$$

where, for convenience, the non-time varying terms are grouped into two constants K_C and K_S as follows:

$$K_C = \left[B_1B_2 + A_1A_2\right] \cos(\theta) \tag{15}$$

$$K_S = \left[A_1B_2 + B_1A_2\right] \sin(\theta) \tag{16}$$

Since we have set the transmitted signal power Ps of s(t) equal to 1 (equation (3)) and the receive antenna gain to unity (equation (8)), then the time-averaged output signal power Prcv in Figure 3 represents the polarization mismatch loss or antenna coupling efficiency. A value of 1 indicates no polarization mismatch loss, while Prcv = 0 indicates infinite polarization isolation between the two antennas.

Let F denote the coupling efficiency between the two antennas. Then:

$$F = \text{Prcv} = \lim_{T\to\infty} 1/T \int_{-T/2}^{T/2} v_{rcv}^2(t)\, dt = \lim_{T\to\infty} 1/T \int_{-T/2}^{T/2} \left[K_C\cos(\omega t+\varphi) + K_S\sin(\omega t+\varphi)\right]^2 dt$$

$$= \left[K_C^2 + K_S^2\right]/2 \qquad (17)$$

Substituting expressions for K_C and K_S from equations (15) and (16) yields:

$$F = (1/2)\left[(B_1B_2 + A_1A_2)^2 \cos^2(\theta) + (A_1B_2 + B_1A_2)^2 \sin^2(\theta) \right]$$

$$= (1/2)\left\{ 2A_1A_2B_1B_2\left[\cos^2(\theta) + \sin^2(\theta)\right] + \cos^2(\theta)(A_1^2A_2^2 + B_1^2B_2^2) + \sin^2(\theta)(A_1^2B_2^2 + B_1^2A_2^2) \right\} \qquad (18)$$

We now make the following trigonometric substitutions:

$$\cos^2(\theta) + \sin^2(\theta) = 1 \qquad (19)$$

$$\cos^2(\theta) = (1/2)\left[1 + \cos(2\theta) \right] \qquad (20)$$

$$\sin^2(\theta) = (1/2)\left[1 - \cos(2\theta) \right] \qquad (21)$$

Substituting equations (19), (20), and (21) into (18), and rearranging terms yields:

$$F = (1/4)\left[4A_1A_2B_1B_2 + A_1^2A_2^2 + B_1^2B_2^2 + A_1^2B_2^2 + B_1^2A_2^2 + \cos(2\theta)\left(A_1^2A_2^2 + B_1^2B_2^2 - A_1^2B_2^2 - B_1^2A_2^2\right) \right] \qquad (22)$$

Finally, substituting the expressions for A_1, A_2, B_1, and B_2 from equations (4), (5), (9), and (10), into (22) and simplifying gives the final expression for coupling efficiency F in terms of axial ratios r_1 and r_2, and the angle θ between the 2 antenna major axes:

$$F = \frac{4r_1r_2 + (r_1^2+1)(r_2^2+1) + (1-r_1^2)(1-r_2^2)\cos(2\theta)}{2\,(r_1^2+1)\,(r_2^2+1)} \qquad \text{(same sense pol.)} \qquad (23)$$

Recall that both antennas #1 and #2 were defined as having right-hand polarization sense. Therefore, equation (23) is valid for same-sense polarization. To determine the corresponding expression for opposite-sense polarization, either the input signal s(t) or receive antenna #2 can be redefined as having left-hand polarization sense. For example, the expression for s(t) from equation (2) now becomes:

$$s(t) = -A_1 \sin(\omega t + \varphi)\underline{\underline{\mathbf{x}}} + B_1 \cos(\omega t + \varphi)\underline{\underline{\mathbf{y}}} \qquad \text{(left-hand sense)} \qquad (24)$$

Alternatively, the receive antenna in Figure 2 can be converted to left-hand polarization sense by changing the phase shift of the major axis component from $+90^o$ to -90^o. The expression for antenna coupling efficiency F was thus re-derived for the opposite-sense case using the same steps as described above for the same-sense derivation. The resulting expression for F was found to be identical to equation (23) except that the "$4r_1r_2$" term in the numerator becomes subtractive rather than additive.

The preceding results lead to the following general expression for F that can be used for both same and opposite polarization sense:

$$F = \frac{4Kr_1r_2 + (r_1^2 + 1)(r_2^2 + 1) + (1 - r_1^2)(1 - r_2^2)\cos(2\theta)}{2(r_1^2 + 1)(r_2^2 + 1)} \qquad (25)$$

where:

- F = coupling efficiency.
- r_1 = antenna #1 voltage axial ratio $(1 \le r_1 \le \infty)$.
- r_2 = antenna #2 voltage axial ratio $(1 \le r_2 \le \infty)$.
- θ = angle between major axes of the 2 antennas.
- K = 1 for same-sense polarization, = -1 for opposite sense.

Some Cases of Interest:
Using equation (25), Table1 below shows the polarization mismatch loss for several specific polarization scenarios of interest:

Table 1: Polarization Mismatch Loss for Specific Antenna Configurations

Scenario	r_1	r_2	θ	Sense	Pol. Loss (dB)
Linear ↔ Linear	∞	∞	θ-variable	N/A	$20 \log[\cos(\theta)]$
Linear ↔ Circular	∞	1	N/A	N/A	-3.0
Elliptical ↔ Linear	4 (6 dB)	∞	90^o	N/A	-12.3
Elliptical ↔ Circular	4 (6 dB)	1	N/A	same	-1.3
Elliptical ↔ Circular	4 (6 dB)	1	N/A	opposite	-5.8

Exhibit 2

Recreated from Source: Technical Analysis of Ligado Interference Impact on Iridium User Links; September 1, 2016
Source table values are redacted. Approximated

Table 2: Recreated for MSS Interference Results	MSS	
Frequency	1626.5	MHz
MSS terminal OOBE limit*	-47.2	dBW/4kHz
	-38.4	dBW/30kHz
Separation Distance	13,000	m
Free Space Path Loss	118.9	dB
Iridium Receiver Antenna Gain at Horizon	-3	dBi
Received Interference Power Density	-160.4	dBW/30kHz
Iridium User Terminal Noise Floor	-154.8	dBW/30kHz
I/N	-6	dB
Required I/N	-6	dB
Margin	0	dB

*2003 ATC order (FCC 03-15) states that the Big LEO systems must be capable of tolerating emissions that range from -47 dBW/4KHz to –58 dBW/4kHz